

Where do “red and dead” early-type void galaxies come from?

Darren J. Croton¹, Glennys R. Farrar²

¹*Department of Astronomy, University of California, Berkeley, CA, 94720, USA*

²*Center for Cosmology and Particle Physics, Department of Physics, New York University, New York NY 10003*

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ABSTRACT

Void regions of the Universe offer a special environment for studying cosmology and galaxy formation, which may expose weaknesses in our understanding of these phenomena. Although galaxies in voids are observed to be predominately gas rich, star forming and blue, a sub-population of bright red void galaxies can also be found, whose star formation was shut down long ago. Are the same processes that quench star formation in denser regions of the Universe also at work in voids?

We compare the luminosity function of void galaxies in the 2dF Galaxy Redshift Survey, to those from a galaxy formation model built on the Millennium Simulation. We show that a global star formation suppression mechanism in the form of low luminosity “radio mode” AGN heating is sufficient to reproduce the observed population of void early-types. Radio mode heating is environment independent other than its dependence on dark matter halo mass, where, above a critical mass threshold of approximately $M_{\text{vir}} \sim 10^{12.5} M_{\odot}$, gas cooling onto the galaxy is suppressed and star formation subsequently fades. In the Millennium Simulation, the void halo mass function is shifted with respect to denser environments, but still maintains a high mass tail above this critical threshold. In such void halos, radio mode heating remains efficient and red galaxies are found; collectively these galaxies match the observed space density without any modification to the model. Consequently, galaxies living in vastly different large-scale environments but hosted by halos of similar mass are predicted to have similar properties, consistent with observations.

Key words: galaxies: statistics, galaxies: evolution, galaxies: active, large-scale structure of the Universe

1 INTRODUCTION

According to conventional cosmology, voids provide a special laboratory for studying galaxy formation, in which the dark matter density is locally that of a low density Universe. Peebles has claimed (Peebles 2001) that Λ cold dark matter (Λ CDM) simulations overproduce void galaxies in comparison to observation and he suggested that this may be evidence of as-yet-undiscovered fundamental physics not included in Λ CDM cosmology. Previous work has laid the groundwork for examining this question quantitatively (e.g. Mathis & White 2002; Benson et al. 2003b; Mo et al. 2004; Croton et al. 2004, 2005; Hoyle & Vogeley 2004; Hoyle et al. 2005; Rojas et al. 2004, 2005; Colberg et al. 2005; Goldberg et al. 2005; Clemens et al. 2006; Xia et al. 2006; Patiri et al. 2006; Sorrentino et al. 2006; von Benda-Beckmann & Müller 2008). In Croton et al. (2005) we introduced a practical definition of the void luminosity function and measured it

for early- and late-type galaxies in the 2dF Galaxy Redshift Survey (2dFGRS). Here, we investigate whether Λ CDM simulations can describe the observed void luminosity functions quantitatively, or whether new physics may be required.

State-of-the-art modelling is not sufficiently advanced to treat all the physical processes of galaxy formation from first principles. Here we adopt a semi-analytic approach (White & Frenk 1991) in which the Millennium Simulation of dark matter is coupled with an analytic simulation for baryonic evolution in a cosmologically evolving background. A simplifying approximation made in the current generation of semi-analytic models is that the process of galaxy formation depends only indirectly on the environment or age of a given dark matter halo, via their impact on the halo mass function. While this clearly cannot be exactly true (e.g. Croton et al. 2007), it is interesting to ask whether such simplified models are capable of reproducing the observed luminosity distributions of early- and late-type galaxies in

voids within the observational uncertainties. As we show in the following, the answer is affirmative.

Key to the success of semi-analytic models in describing the global galaxy luminosity function is the presence of heating mechanisms to shut off star formation (Benson et al. 2003a). The exact processes operating are currently subject to some debate. What is not in dispute is the observational evidence of galaxies at the bright-end of the galaxy luminosity function with ongoing, low-luminosity active nuclei. It is thus no surprise that most current semi-analytic models incorporate active galactic nuclei (AGN) heating as a key ingredient. Croton et al. (2006) called this the “radio mode” of AGN evolution. Another process which can shut off star formation in subhalos is the stripping of gas when a satellite falls into a larger halo, called “strangulation”.

There is clear evidence of a population of “red and dead” early-type galaxies¹ even in voids (Croton et al. 2005), yet it is not obvious whether either or both of these mechanisms (i.e. AGN heating and strangulation) can operate efficiently in voids or whether some other mechanism is needed. We investigate this question via semi-analytic simulations, and find that strangulation plays a minor role. We find that heating when the central galaxy passes the critical mass is sufficient to account for the observed abundance of early-type galaxies in voids. The different luminosity functions of early-type galaxies between voids and mean density environments can thus be entirely attributed to the difference in the halo mass function in the two environments, within the accuracy of present measurements. This explanation for the early-type luminosity function has observable consequences as discussed below. If these are verified, it will lend credence to the physical interpretation of the semi-analytic model.

This paper is organised as follows. Sections 2 and 3 describe the galaxy formation model and our measure of environment within the Millennium Simulation, respectively. We present our void galaxy analysis in Section 4 and discuss our results in light of recent work and also within the broader context of galaxy formation theory. Finally, Section 5 provides a brief summary. Throughout we assume a standard WMAP first year Λ CDM cosmology (Spergel et al. 2003; Seljak et al. 2005) and Hubble parameter $H_0 = 100 h^{-1} \text{kms}^{-1} \text{Mpc}^{-1}$.

2 THE GALAXY FORMATION MODEL

The galaxy formation model we use to study void environments is identical to that described in Croton et al. (2006) (including parameter choices). This model is implemented on top of the Millennium Run Λ CDM dark matter simulation (Springel et al. 2005). Below we briefly outline the relevant aspects of the simulation and model to our current work, and refer the interested reader to the above references for further information.

The Millennium Run simulation follows the dynamical evolution of 10^{10} dark matter particles in a periodic box of side-length $500 h^{-1} \text{Mpc}$ with a mass resolution per

particle of $8.6 \times 10^8 h^{-1} \text{M}_\odot$. It adopts cosmological parameter values consistent with a combined analysis of the 2dFGRS (Colless et al. 2001) and first year WMAP data (Spergel et al. 2003; Seljak et al. 2005). Friends-of-friends (FOF) halos are identified in the simulation using a linking length of 0.2 the mean particle separation, while substructure *within* each FOF halo is found with an improved and extended version of the SUBFIND algorithm of Springel et al. (2001). Having determined all halos and subhalos at all output snapshots, the hierarchical merging trees are constructed; these describe in detail how structures grow as the universe evolves. These trees form the backbone onto which we couple our model of galaxy formation.

Inside each tree, virialised dark matter halos at each redshift are assumed to attract ambient gas from the surrounding medium, from which galaxies form and evolve. Our model effectively tracks a wide range of galaxy formation physics in each halo using simple parametrised forms, including reionization of the inter-galactic medium at high redshift, radiative cooling of hot gas and the formation of cooling flows, star formation in the cold disk and the resulting supernova feedback, black hole growth and AGN feedback through the ‘quasar’ and ‘radio’ epochs of AGN evolution, metal enrichment of the inter-galactic and intra-cluster medium, and galaxy morphology shaped through mergers and merger-induced starbursts. At $z=0$ the galaxy formation model contains approximately 9 million galaxies brighter than our completeness limit of $M_{\text{BJ}} - 5 \log_{10} h = -15.8$ (representing the mean luminosity of a central galaxy in a halo containing 64 particles).

A critical feature for the success of this model is the inclusion of an AGN component and the separation of AGN into their high and low accretion states, called the “quasar mode” and “radio mode” respectively. Within this picture the two AGN modes are distinct in their cause and effect. Importantly for the work of Croton et al. (2006), the radio mode was used to suppress the cooling of gas onto central galaxies living in group and cluster-sized halos, and is primarily important at late times (typically $z < 1$) and not earlier (where the SFR density of the universe peaks, e.g. Madau et al. 1996). This model was tuned to provide a good match to the local luminosity function and colours of galaxies. The assumed radio mode black hole accretion rate,

$$\dot{m}_{\text{BH}} \propto m_{\text{BH}} f_{\text{hot}} V_{\text{vir}}^3, \quad (1)$$

is very efficient above a critical halo mass threshold which is approximately constant with time. This mass turns out to be $M_{\text{vir}} \approx 10^{12-13} \text{M}_\odot$. From this point-of-view, halos grow with time until they cross the critical halo mass, after which the radio mode dominates, cooling gas slows, then stops, and star formation shut-down follows. Note that no environment dependence has been assumed in this implementation of radio mode heating. We will return to this point in Section 4.

3 ESTIMATING LOCAL DENSITIES

To facilitate a fair comparison between the model and observed luminosity functions we determine environments in the Millennium Simulation box in the same way as Croton et al. (2005) did for the 2dFGRS. This is actually much simpler to do than with a magnitude limited redshift

¹ The term “red and dead” refers to those galaxies on the red sequence which have had no active star formation in the last several Gyr

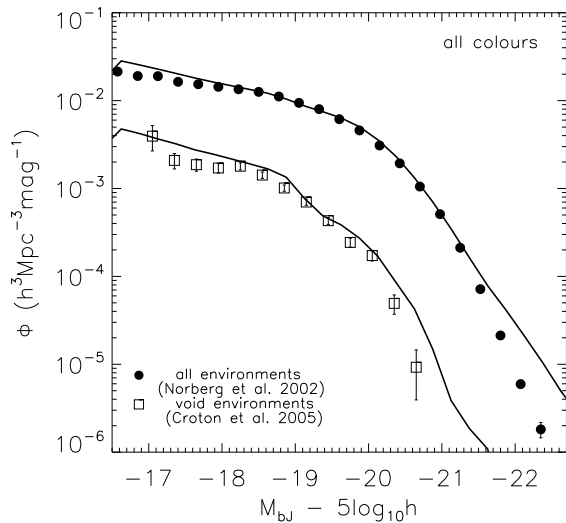


Figure 1. The galaxy luminosity functions for all environments (filled circles, Norberg et al. 2002) and in void regions exclusively (open squares, Croton et al. 2005), both from the 2dFGRS. The matching solid lines indicate the semi-analytic model result analysed in the same way. The model is tuned for good agreement with the global 2dFGRS luminosity function; from this alone the distribution of galaxy magnitudes in voids is also reproduced.

survey, as one has a perfect measure of survey geometry (a box in our case with volume V_{box}) and selection function (uniform and complete). We consider the redshift zero snapshot of the model, which we call the “local” population. Note that, although the 2dFGRS has a median redshift of $z \sim 0.1$, all 2dFGRS magnitudes are k-corrected to $z=0$, and for our purposes we assume that the evolution of structure between $z=0.1$ and $z=0$ is negligible. All model galaxies are shifted into redshift space using the distant observer approximation.

Environments are measured using the smoothed top-hat number density contrast around each galaxy. As in Croton et al. (2005), we define a *density defining population* (DDP) of galaxies which fix the density contours in the redshift space volume containing the model galaxies; this is simply all galaxies in the magnitude range $-19 > M_{\text{BJ}} - 5 \log_{10} h > -22$. We then consider *all* galaxies in turn, counting the number of DDP neighbours within a sphere of $8 h^{-1} \text{Mpc}$ radius, N_g . This scale was found by Croton et al. (2005) to optimise the simultaneous sampling of both the under- and over-dense regions of the survey in a consistent way. The mean number density of the DDP is known, $\bar{\rho}$, and thus the expected mean number within $8 h^{-1} \text{Mpc}$ is also known, $\bar{N}_g = \bar{\rho} \frac{4}{3} \pi 8^3$. Hence, the density contrast, δ_8 , for each galaxy is simply

$$\delta_8 \equiv \frac{\delta \rho_g}{\rho_g} = \frac{N_g - \bar{N}_g}{\bar{N}_g} \bigg|_{R=8h^{-1}\text{Mpc}}. \quad (2)$$

The Millennium Simulation was run using periodic boundary conditions, and hence we do not need to worry about boundary effects in our semi-analytic model galaxy catalogue or δ_8 calculation.

To determine the volume fraction that voids occupy in

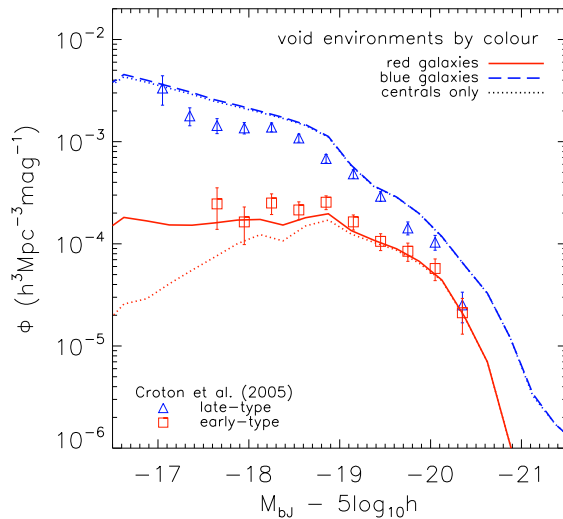


Figure 2. The galaxy luminosity function in voids, now broken into their blue/late-type and red/early-type sub-populations (see figure legend). The dotted lines show the model luminosity functions for central galaxies only, i.e. when satellites are removed (see Section 4.2). Both red and blue sequence model galaxies have similar luminosity distributions to the 2dFGRS data. The model early-type void population is dominated by central galaxies.

the Millennium Simulation we fill the simulation box with a large number of randomly placed points, and for each we determine the number of DDP galaxies within $8 h^{-1} \text{Mpc}$. This provides a uniform sampling of δ_8 via Equation 2 throughout the box. The fraction of random points in a δ_8 range provides the volume filling fraction that this environment occupies. This allows us to appropriately normalise the number density of galaxies in that environment when calculating each luminosity function. This method is described in detail in Appendix A of Croton et al. (2005).

4 RESULTS AND DISCUSSION

4.1 The void luminosity function

We begin with Figure 1, which shows the luminosity function of model galaxies for both the population as a whole, and all galaxies in void regions. Here we define a void as Croton et al. (2005) did, $\delta_8 < -0.75$, i.e. where the density within an $8 h^{-1} \text{Mpc}$ radius of the galaxy is less than 25% the mean. Over-plotted are the observational results for the full 2dFGRS (filled circles, Norberg et al. 2002) and void galaxy luminosity function (open squares, Croton et al. 2005).

As was the focus of Croton et al. (2006), the global luminosity distribution of model galaxies is a good match to the local observations. Important model ingredients that produced this result are the supernova in shallower potentials that expel disk gas to reduce star formation and flatten the faint-end slope, and the inclusion of an AGN heating source in large halos to starve massive central galaxies of star forming fuel, resulting in the observed bright-end exponential cut-off, as described in Section 2. Without these two critical aspects in the model, the luminosity function instead

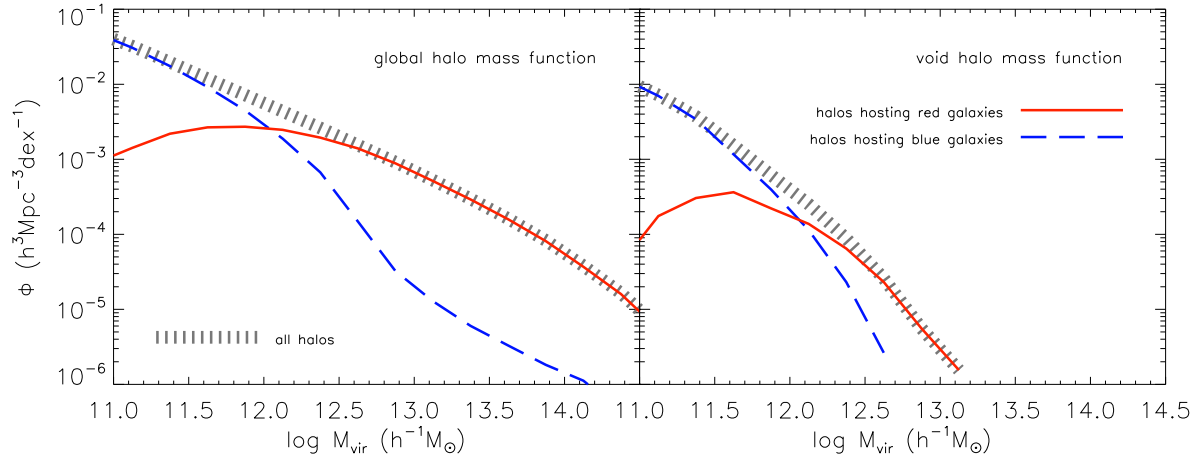


Figure 3. The Millennium Simulation halo mass function (left panel) and halo mass function in voids (right panel). In both panels the halo mass function is broken up into those who host red central galaxies (solid lines) and those that host blue central galaxies (dashed lines). Red sequence galaxies occupy the most massive halos in all environments – these halos are subject to the radio mode low luminosity AGN heating that ultimately shuts down star formation. Notably, this shutdown begins at approximately the same mass in both panels, $M_{\text{vir}} \sim 10^{12-12.5} M_{\odot}$. This implies that the (environment independent) radio mode heating, plus a shift in the halo mass function with environment, is sufficient to reproduce the observed abundance of void early-type galaxies seen in Figure 2.

would have a power-law shape reflecting the underlying mass function of halos (Benson et al. 2003a).

Note that there remain discrepancies in the top curve of Figure 1, notably that the model over-predicts the abundance of very bright galaxies. As discussed in Croton et al. (2006), these galaxies represent a population undergoing strong star formation and merger-induced starbursts. In such ultraluminous infrared galaxies (ULIRGs), nearly all the light from young stars is absorbed by dust and re-radiated in the mid- to far-infrared (Sanders & Mirabel 1996). Improved modelling of the effects of dust are required to adequately reproduce the properties of such systems.

The lower solid line in Figure 1 shows the model result for the void galaxy population in the Millennium Simulation. The good overall agreement is a result of the physical prescriptions and global parameter choices in the Croton et al. (2006) model and not additional fine-tuning (of which there was none). There is some over-prediction of the very brightest void galaxies. However the discrepancy is not significant enough to expect that improvements to existing aspects of the model, e.g. dust as described above, cannot alleviate such differences. Additionally, we find a small over-prediction of faint ($M_{\text{bJ}} - 5 \log_{10} h \gtrsim -18.5$) galaxies. Unfortunately, systematic variations in the observed faint-end galaxy luminosity function exist at a level greater than this (e.g. contrast Cole et al. 2001 to Huang et al. 2003).

Figure 1 alone answers the challenge posed by Peebles and outlined in the Introduction. Specifically, in a Λ CDM Universe the distribution of dark matter halos in voids, coupled with a realistic model of galaxy formation, is consistent with voids as observed in the real Universe. Such regions are typically not devoid of galaxies as claimed in Peebles (2001).

The remainder of this letter will aim to dissect and understand the good agreement shown in Figure 1 between model and observation.

4.2 Galaxy colours in voids

The colour of a galaxy tells us a lot about the relevant physics that has been dominant during its evolution. A red spectrum typically indicates that a star formation shutdown mechanism has been operating for a significant part of the galaxy’s lifetime. We can use this knowledge, in conjunction with our theoretical model, to gain insight into how shutdown may occur and to what degree it may (or may not) be environment specific.

To this end, in Figure 2 we again plot the void galaxy luminosity function for both the 2dFGRS (symbols, Croton et al. 2005) and semi-analytic model (lines), but now broken up by galaxy spectral type (early/late) or colour (red/blue). Early-type (triangles) and late-type (squares) 2dFGRS galaxies are determined using the principal component analysis of Madgwick et al. (2003). For the model we use the bi-modal galaxy colours to separate red (solid line) from blue (dashed line) at $m_{\text{bJ}} - m_{\text{rF}} = 1.07$ (see figure 9 of Croton et al. 2006). Comparing model to observation, Figure 2 shows agreement (to within 2σ) between the two sets of early-type/red and late-type/blue void luminosity functions. This has occurred as a byproduct of matching the model to the observed *global* properties and only these – no special void environment physics was needed. Adding detail to the physical prescriptions assumed by the model would presumably improve the agreement further, but this is not our focus here.

The early-type 2dFGRS void galaxies in Figure 2 return our focus to the question asked in the Introduction: how does one understand early-type galaxies in voids when void environments are typically very gas rich and slowly evolving, which tends to promote star formation rather than suppress it. At this point it may be valuable to backtrack somewhat and revisit the two main mechanisms acting in the model that can turn blue galaxies red. The first is important for satellite (i.e. non-central) galaxies. Upon infall into a more

massive system, any extended hot gas around the (now) satellite is stripped by the denser medium and added to the more massive halo. Such “strangulation” drives a satellite galaxy to redden rapidly once its remaining cold disk gas is exhausted. The second is the radio mode heating discussed above and in Section 2. Radio mode AGN operate only in central galaxies where the host halo has grown above a critical mass threshold, approximately $M_{\text{vir}} \sim 10^{12.5} M_{\odot}$.

So what physical processes have occurred to produce in the observed 2dFGRS early-type void population? It may be that such red galaxies are simply a population of satellites and have survived long enough for an effect on their colours to be seen. To test this idea using the model we perform a simple and revealing exercise. From our knowledge of which galaxies are central and which are satellites, we remove those that are satellites and hence those that could have experienced the strangulation effect. This is shown by the dotted lines in Figure 2. Although satellites do contribute to the void early-type luminosity function at $M_{\text{b},j} - 5 \log_{10} h \gtrsim -18.5$, they are clearly a minor component brighter than this. Indeed, all bright early-type void galaxies are centrals in our galaxy formation model.

The second of our star formation shut-down mechanisms, i.e. radio mode low luminosity AGN heating, requires that central galaxies reside in sufficiently large dark matter halos. Such halos are not expected to be common in void regions of the Universe where low mass halos dominate. In low mass halos the central density of hot gas is not high enough to maintain the low Eddington accretion needed to power a central AGN outflow. We check this explicitly in Figure 3, where we plot the halo mass function for halos in all environments (left panel) and void environments (right panel) (wide-dashed lines in both). In addition, we break the halo mass functions into those halos hosting red central galaxies (solid lines) and those hosting blue central galaxies (dashed lines).

Figure 3 reveals the origin of the void early-type population – they are simply central galaxies that live in halos massive enough to have the low luminosity radio mode operating. In other words, the physics assumed by the model that transforms blue galaxies into red operates independent of environment but can still produce the observed environmental trends in voids (note that the transition from blue-dominated to red-dominated dark matter halos begins at approximately the same mass in both panels, $M_{\text{vir}} \sim 10^{12} M_{\odot}$). Specifically, *it is the shift in halo mass function with environment that changes, not the transformation mechanism itself*.

This picture has important consequences for galaxy evolution more generally. First, it indicates the necessity for active galaxies in voids, confirmed in a number of studies (see, e.g., Constantin et al. 2008 at $z \sim 0$, and Montero-Dorta et al. 2008 at $z \sim 1$). Second, it requires that void galaxies should have similar properties to those in all other environments, assuming the galaxies compared are hosted by halos of similar mass. This is a theoretical confirmation of numerous observational studies that have shown that environments on scales larger than a few Mpc (i.e. outside the dark matter halo) are not important for galaxy formation (e.g. see Blanton & Berlind 2007, and references therein). For example, Patiri et al. (2006) investigate the properties of void galaxies in the Sloan Digital Sky

Survey and compare to those of a similarly constructed mock catalogue using the same Croton et al. (2006) model used here. They found little difference in the mean properties of void galaxies relative to the field, specifically in colour, specific star formation rate, and morphology. Theoretically one may expect large-scale environment to be important, e.g. the effect of assembly bias for dark matter halos (Gao et al. 2005). However the galaxy population does not appear to be overly sensitive to this (see, for example, Croton et al. 2007). A similar conclusion was recently arrived at in a complementary analysis by Tinker et al. (2007).

5 SUMMARY

It has been suggested that void environments pose a problem for galaxy formation theory in a Λ CDM universe due to the apparent over-abundance of dark matter halos in voids relative to the observed abundance of galaxies (Peebles 2001). In this paper we show that no conflict exists within the current observational uncertainty.

- Our model can reproduce the observed abundance of void galaxies, both globally and by colour, without any modification or additional environment dependent physics.
- Early-type “red and dead” red sequence galaxies appear naturally in the voids. They arise because of a shift in the halo mass function in low density environments combined with an environment independent star formation shut-down mechanism efficient above a critical halo mass (here, radio mode AGN). Together, these approximately produce the correct observed abundance.
- Some notable consequences follow from our results. For example, at a given host halo mass, void galaxies are expected to have similar properties on average to those in the field, because such galaxies will have had similar evolutionary histories to field and cluster galaxies.

Voids and void galaxies provide an important probe of both cosmology and galaxy formation. Future wide-field surveys will produce large-scale maps of the Universe out to high redshift, from which void evolution can be studied in detail. Such work will further constrain galaxy formation theory, both in under-dense and the wider field environment.

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